Low Energy Measurement Techniques

Dark Matter Silver Jubilee

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The Signal and Main Background

Signal

(or neutrons)

Nucleus Recoils

E_r

$v/c \approx 7\times10^{-4}$

$E_r \approx 10$'s KeV

phonons

χ^0

Background

(gammas)

Electron Recoils

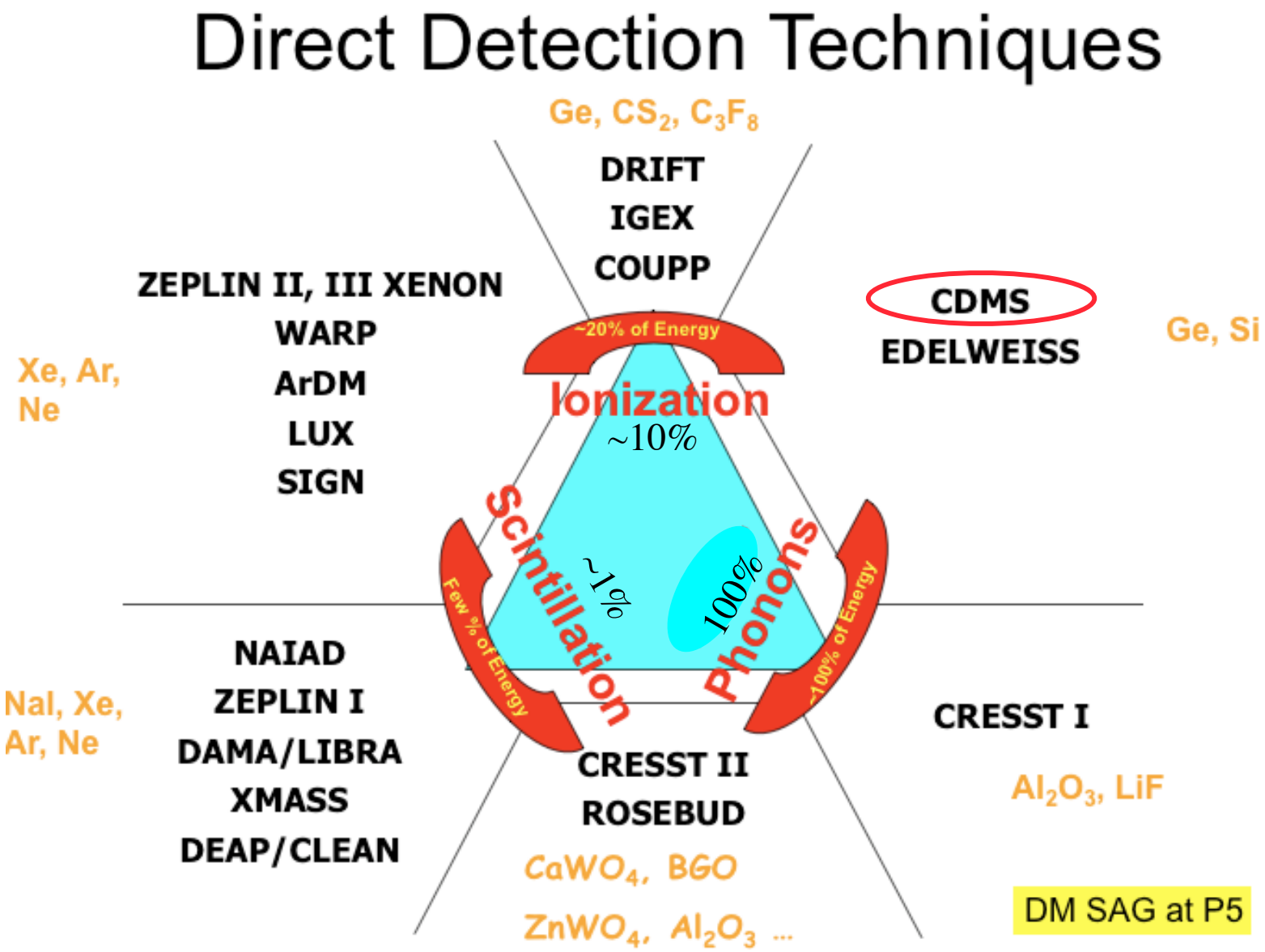
E_r

$v/c \approx 0.3$

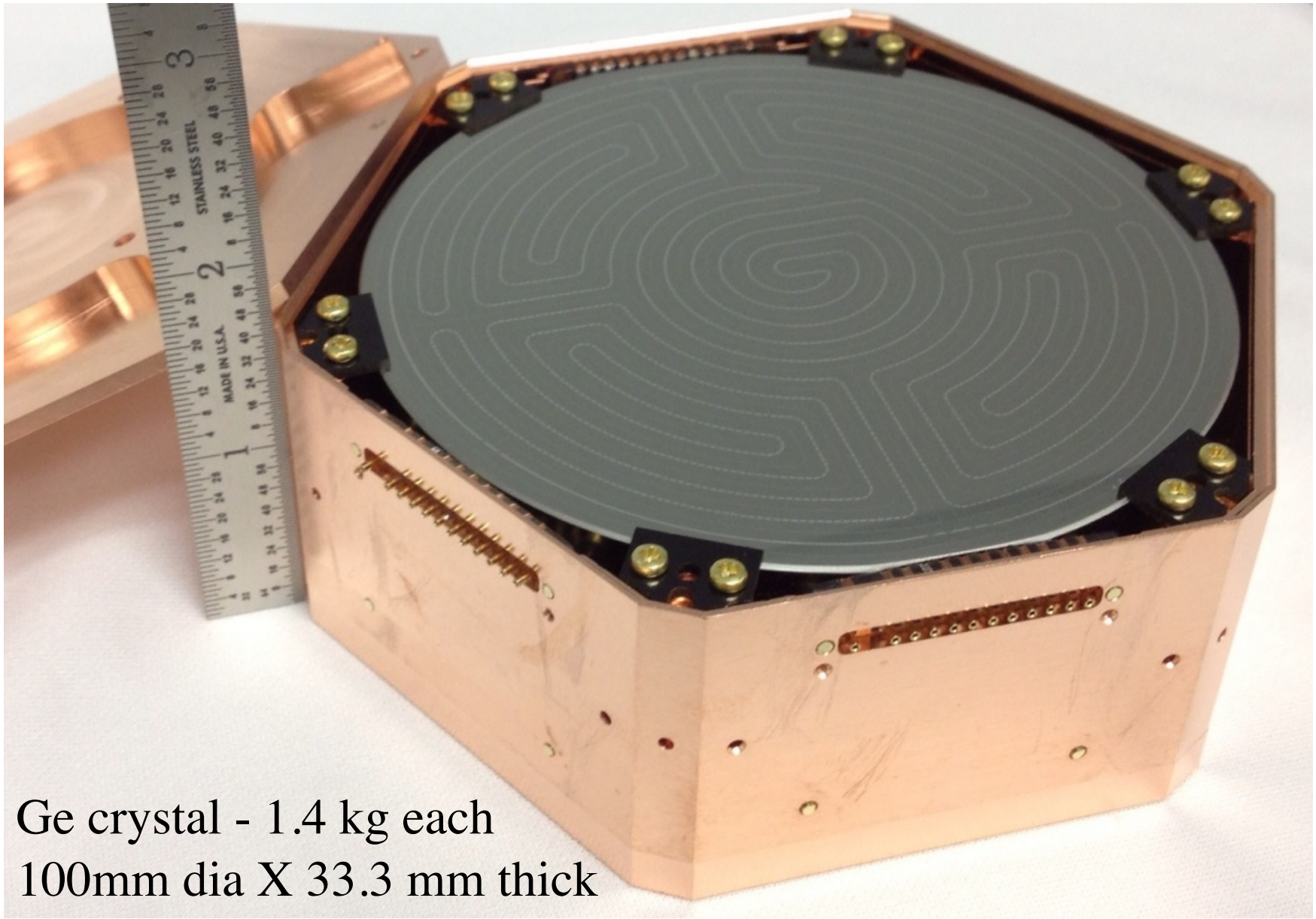
ionization

γ

Discrimination strategies

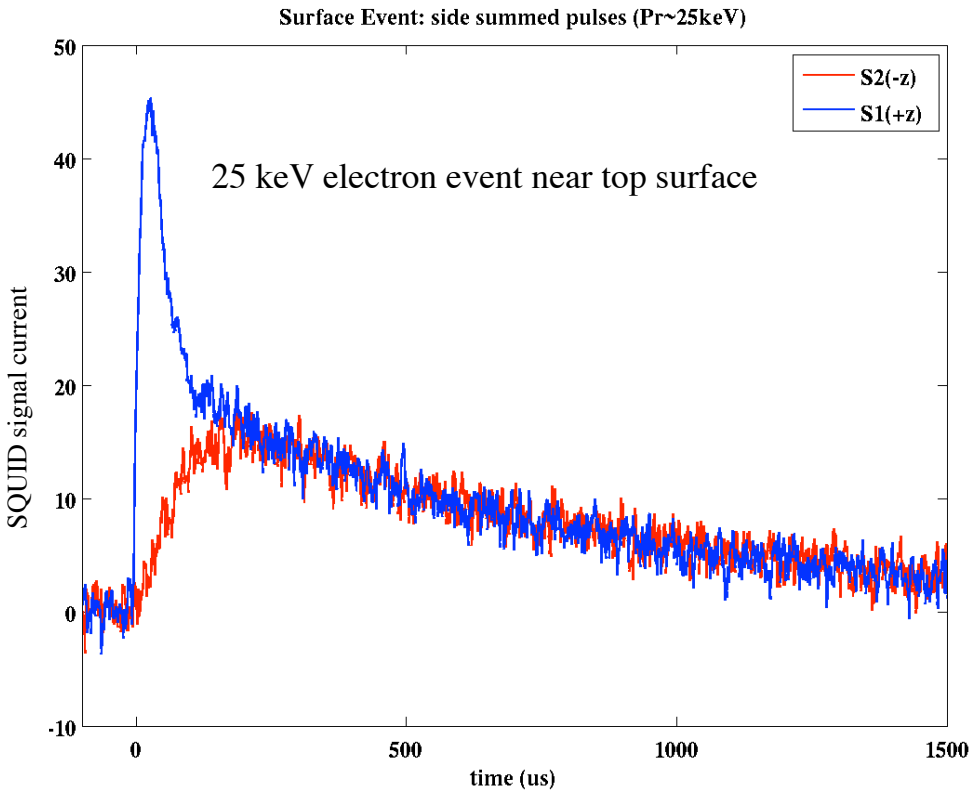


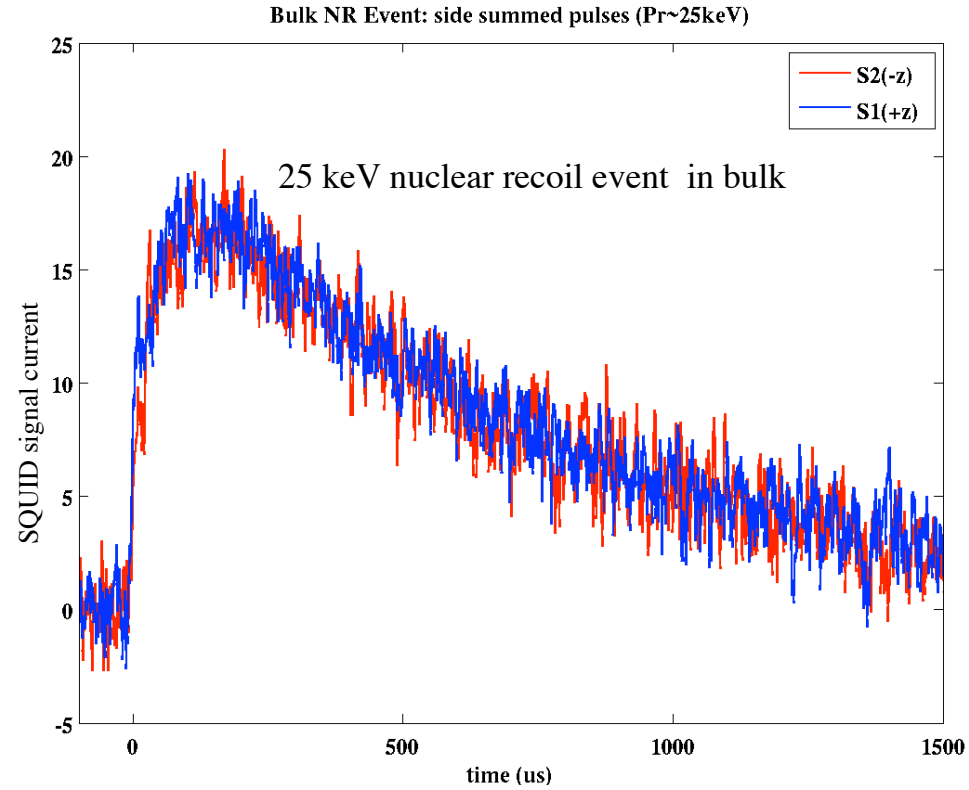
SuperCDMS SNOLAB Detectors



Ge crystal - 1.4 kg each
100mm dia X 33.3 mm thick

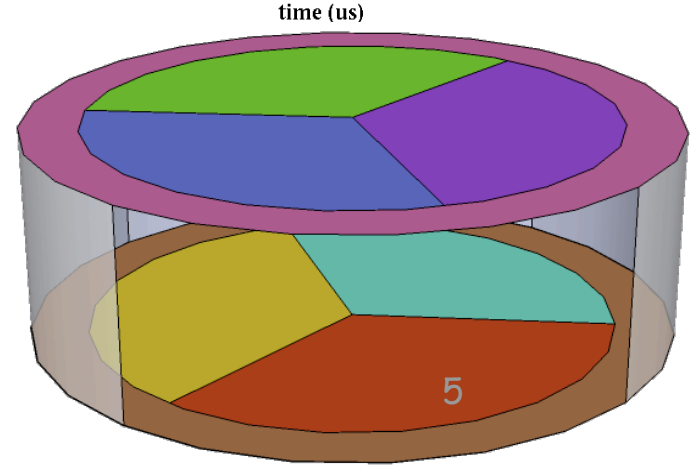
Observed iZIP Phonon Pulse Shape Discrimination



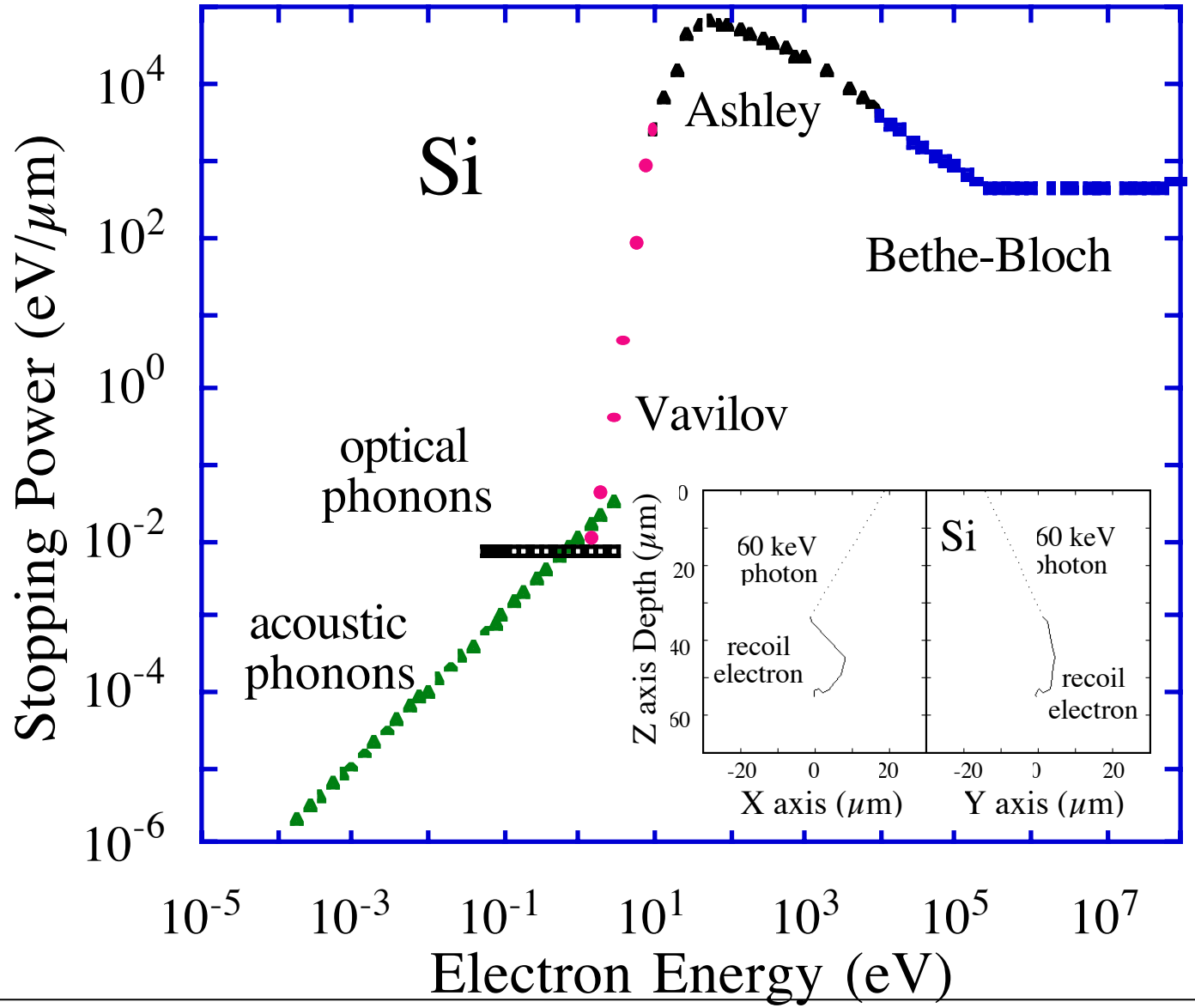


Surface Electron vs Nuclear Recoil discrimination seen in operating iZIP detectors in both pulse shape differences and energy partition in z-direction.

Phonon sensor layout:

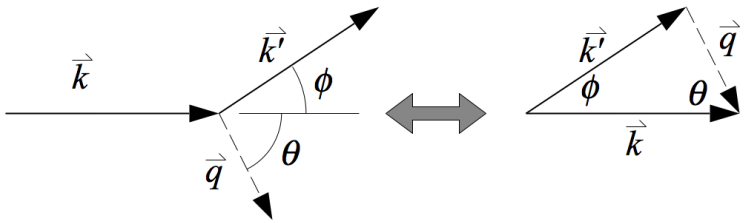


Electron energy loss in Si and Ge

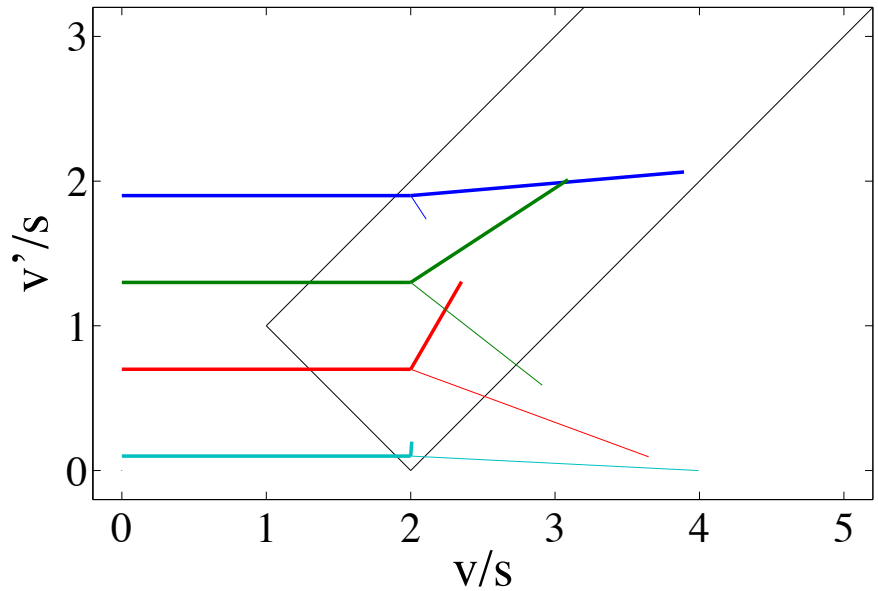


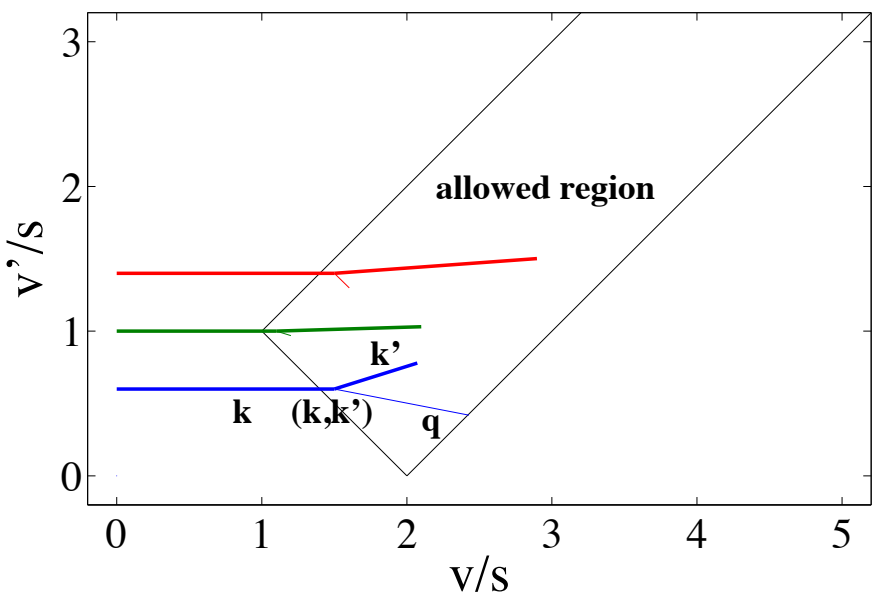
Electrons and holes emitting phonons

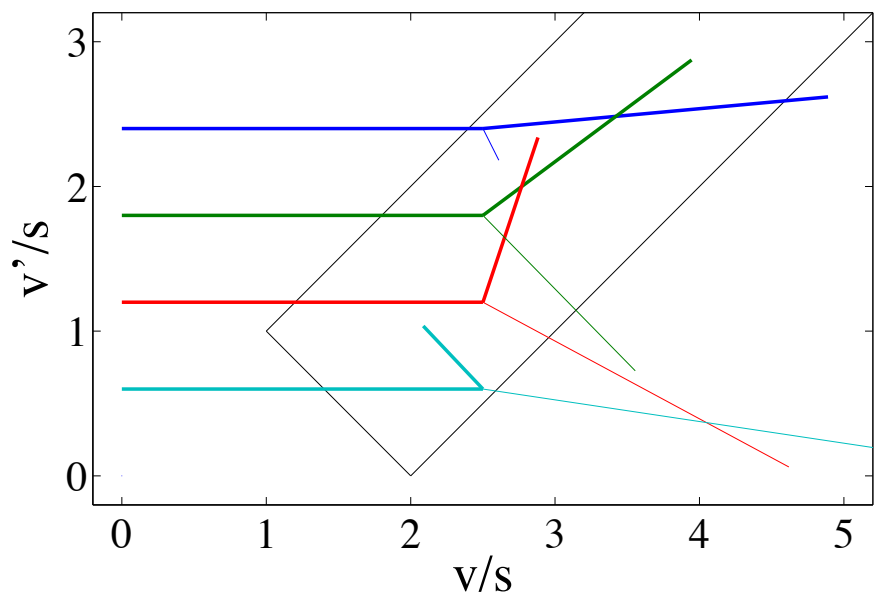
- conserve momentum and energy



$$P_{k,k'\pm q} = \frac{2\pi V}{\hbar} |\langle k' \pm q|H|k\rangle|^2 \delta(E - E' \mp \hbar\omega)$$

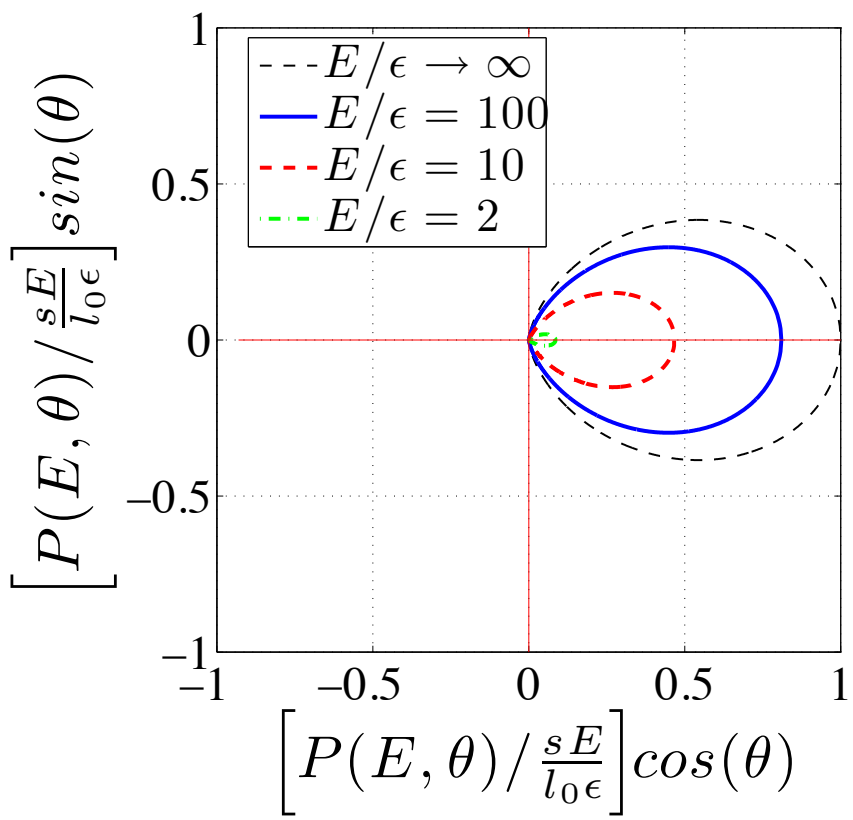


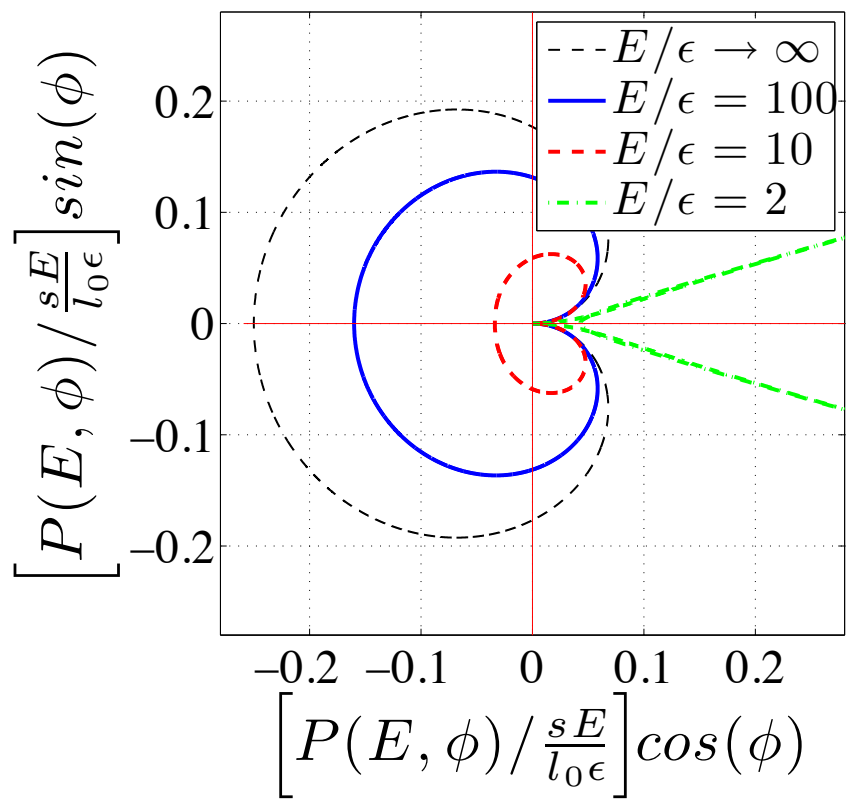




Probability distributions

- theta angle between incident electron and emitted phonon and phi angle between incident and scattered electron





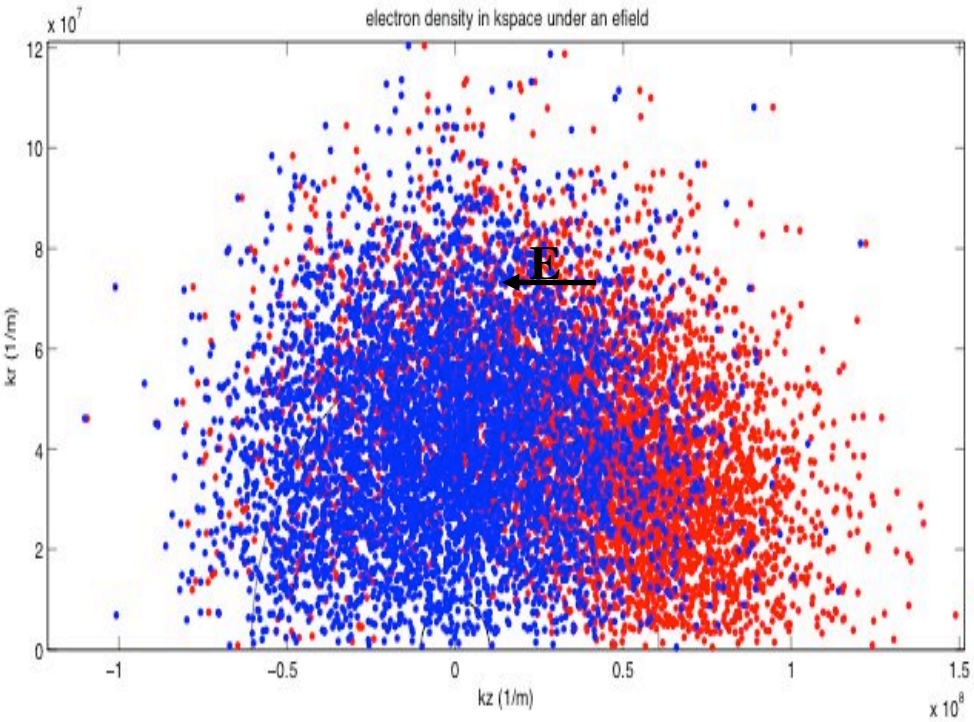
Mean field calculations

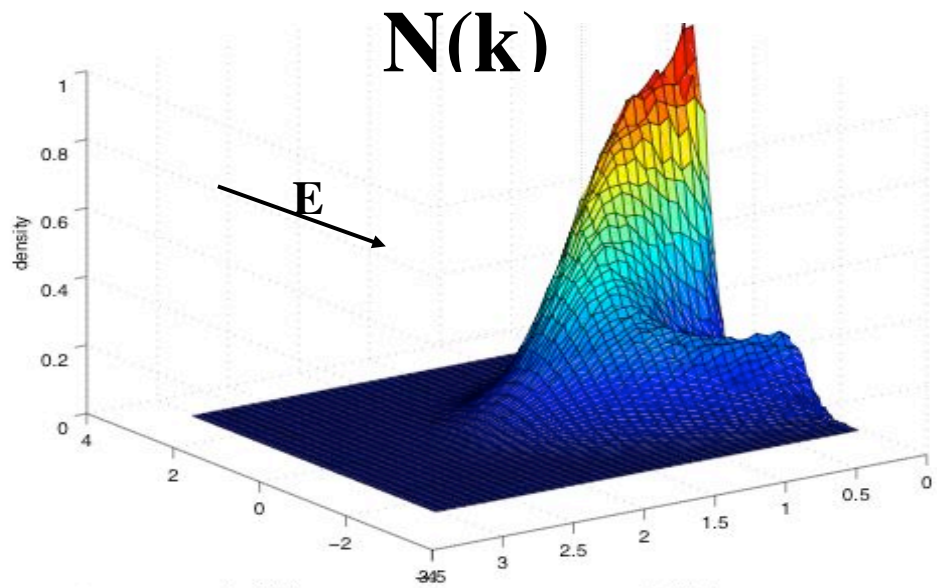
	Silicon		Germanium	
	Electrons	Holes	Electrons	Holes
$m_{\parallel}/m_e$	0.91	0.5	1.58	0.38
$m_{\perp}/m_e$	0.19	0.5	0.081	0.38
m_d/m_e	0.33	0.5	0.22	0.38
m_c/m_e	0.26	0.5	0.12	0.38
s_l (km/s)	9.15		5.4	
ν_D (THz)	~7		~4	
κ	12		16	
ρ (g/cm^3)	2.335		5.323	
$\frac{1}{2}m_d s^2$(K)	0.9	1.4	0.21	0.365
l_0 (μm)	7.5	3.0	2.8	4.3
C_d (eV)	9.26	7.85	13.3	4.73
C_c (eV)	13.2	7.85	33.0	4.73

		Silicon		Germanium	
	units	Electrons	Holes	Electrons	Holes
L	mm	0.3	0.3	10	10
V_0	V	1	1	1	1
$\epsilon = \frac{1}{2}m_d s^2$	μeV	78.6	119	18.2	31.5
$\alpha(V_0) = (eVl_0)/(2\epsilon L)$		159	42.0	76.9	68.3
$v_d = 1.31 s\alpha^{1/5}$	km/s	33.0	25.3	16.9	16.5
$\bar{v} = 1.38 s\alpha^{2/5}$	km/s	95.9	56.3	42.3	40.4
$\bar{E}_q = 4.14\epsilon\alpha^{2/5}$	meV	2.47	2.20	0.43	0.71
$\bar{E} = 1.90\epsilon\alpha^{4/5}$	meV	8.62	4.50	1.12	1.76
$\lambda = 2.17 l_0\alpha^{-2/5}$	μm	2.14	1.46	10.7	17.2
$\lambda_{\parallel} = 2.07 l_0\alpha^{-3/5}$	μm	0.74	0.66	4.28	7.06
$\sigma_{\perp} = 1.7\sqrt{x l_0}\alpha^{-1/10}$	μm	48.6	35.3	583	731
$n = L/\lambda_{\parallel}$		405	455	2340	1420

Matt Pyle MC for Luke phonons

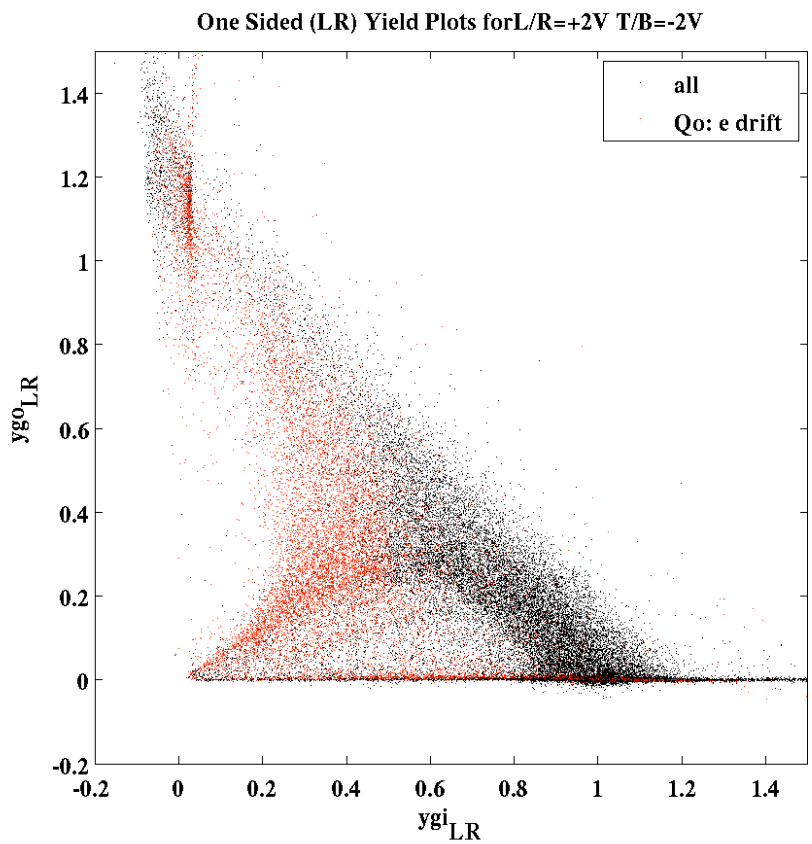
- Used isotropic approximation to propagate electrons and holes and input into stochastic model that follows them as they move and are heated in the electric field.

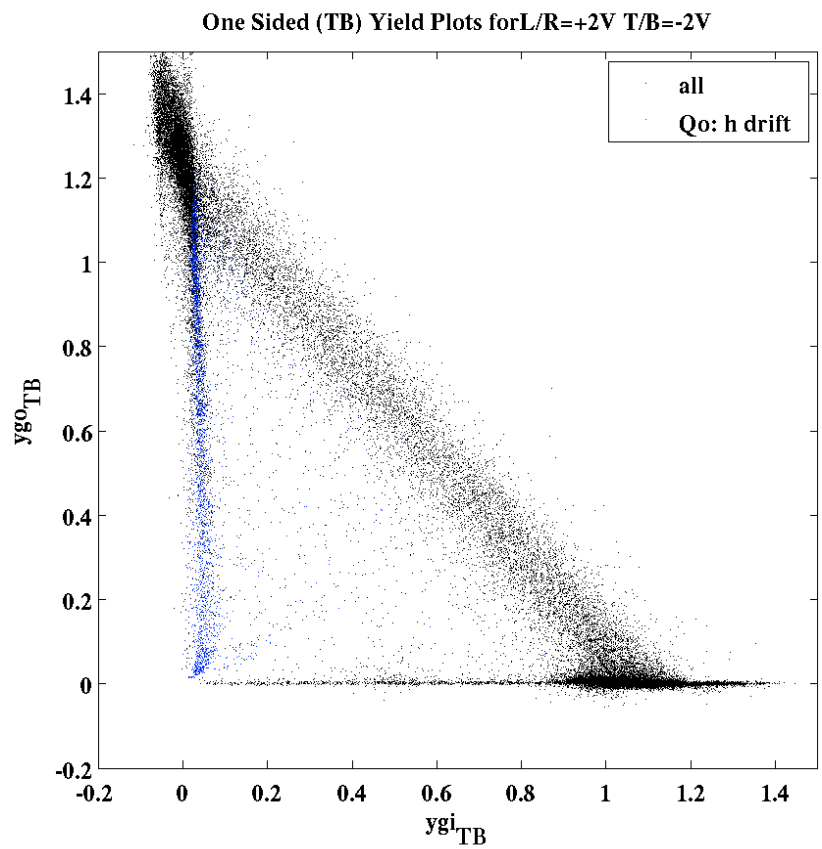




Data different for electrons and holes

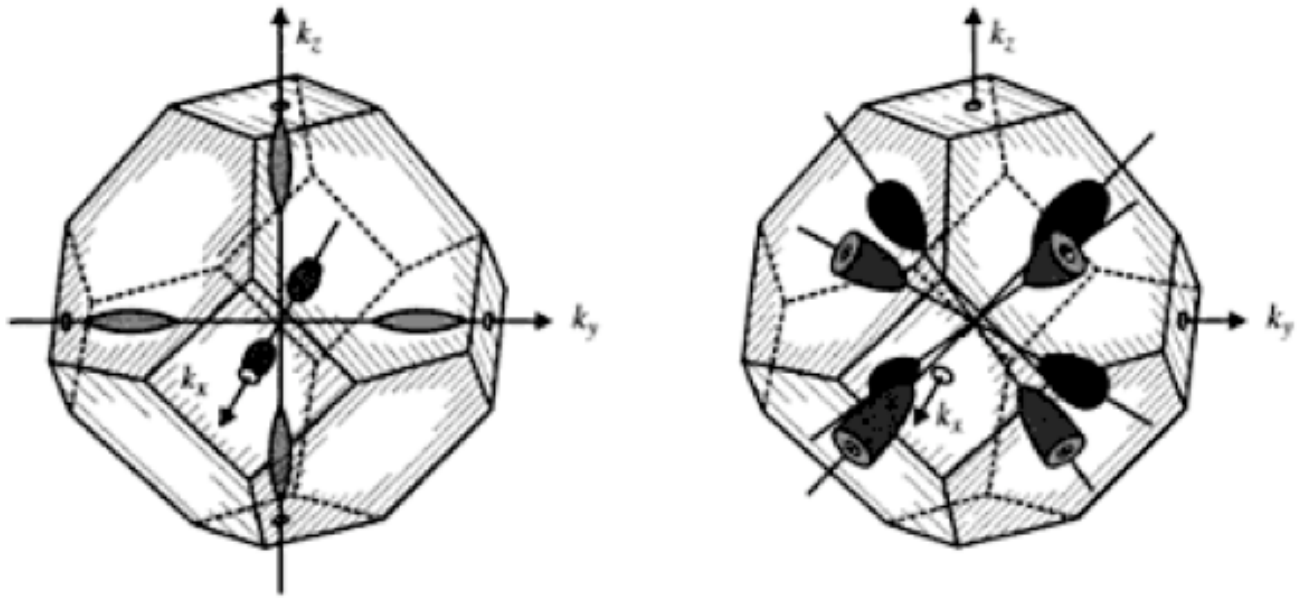
- clear evidence that electrons travel obliquely versus holes that travel more isotropically





Indirect gap semiconductors

- Conduction electrons in valleys along [111] for Ge and have very anisotropic effective masses



- holes have minimum energy at center of zone so behave more isotropically

Model valley energy

- Elliptical potential wells given by

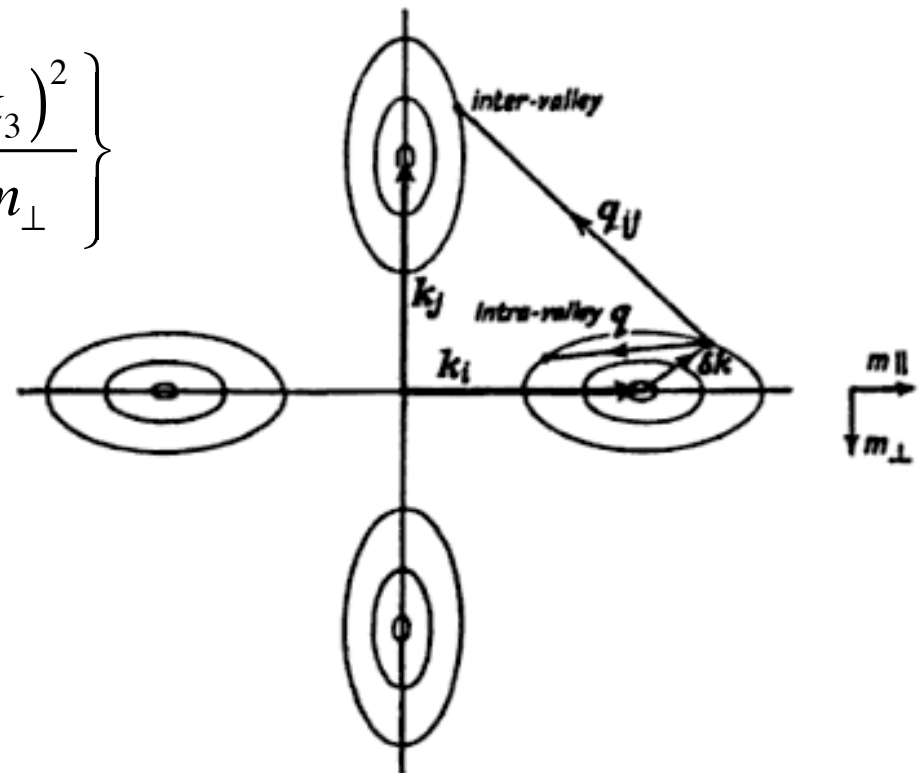
$$\varepsilon_{\vec{k}} = \hbar^2 \left\{ \frac{(\delta k_1)^2}{2m_{\parallel}} + \frac{(\delta k_2)^2}{2m_{\perp}} + \frac{(\delta k_3)^2}{2m_{\perp}} \right\}$$

where for Ge

$$m_{\parallel} = 1.58\, m_e$$

$$m_{\perp} = 0.081\, m_e$$

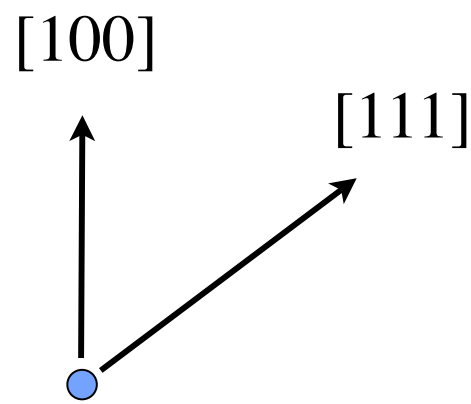
nearly a factor of 20 !



Oblique propagation necessary

- Electric field along [100]

$$e\vec{E} = \frac{d\vec{p}}{dt}$$



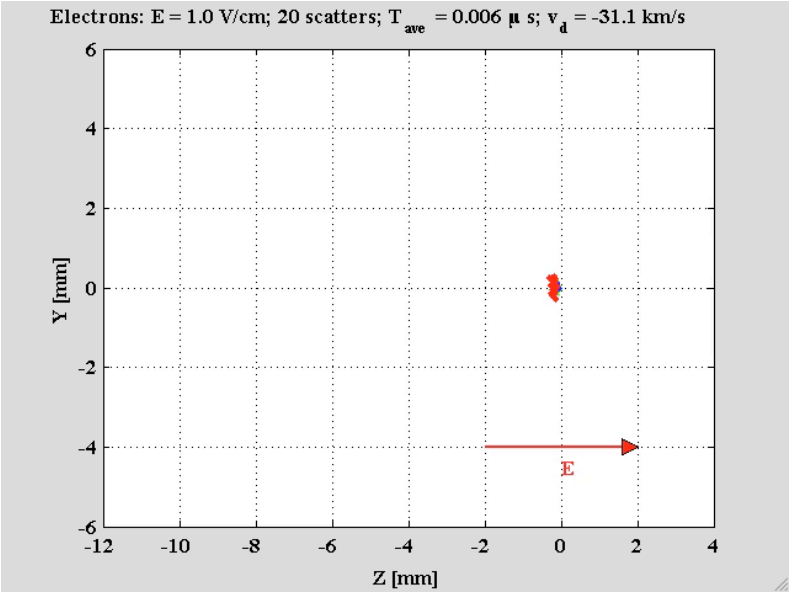
so that change in momentum is along [100] since

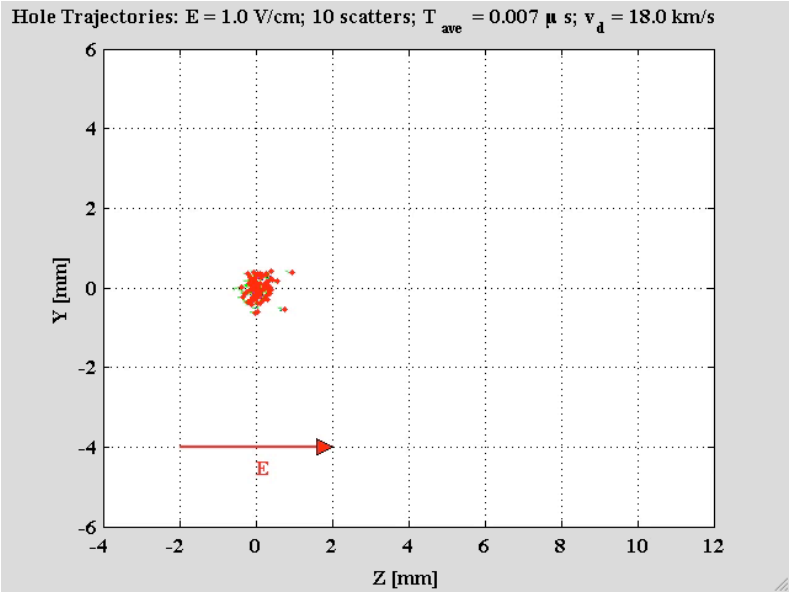
$$\vec{p} = \bar{\bar{m}} \cdot \vec{v} = m_{\perp} v_{\perp} \hat{n}_{\perp} + m_{\|} v_{\|} \hat{n}_{\|}$$

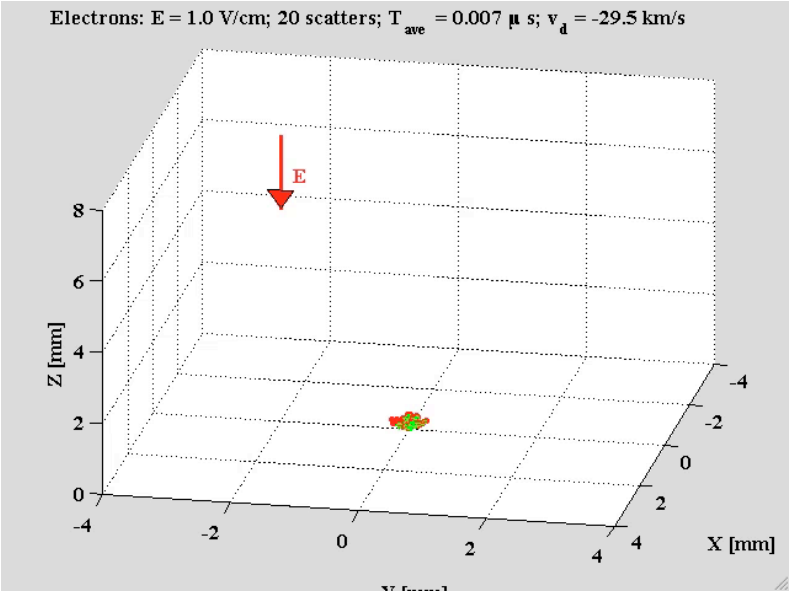
- However, change in velocity is nearly along perpendicular to [111] since

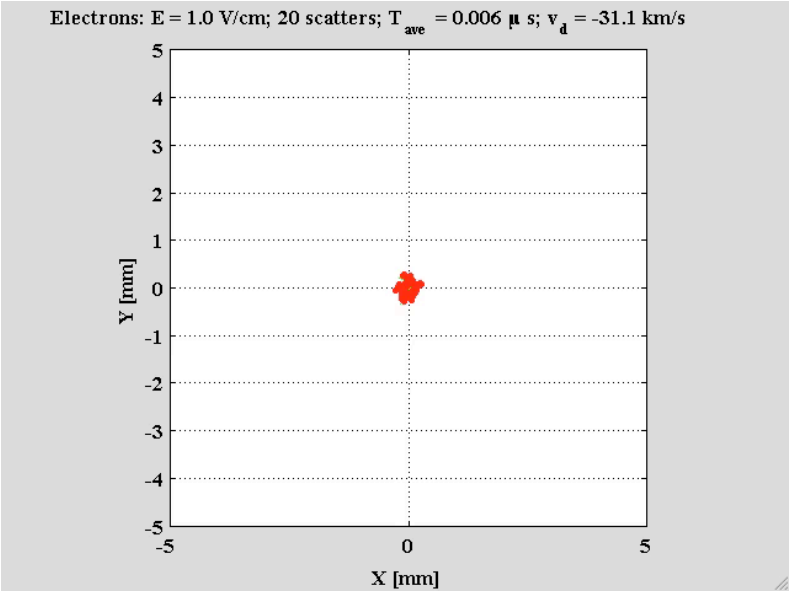
$$\vec{v} = v_{\perp} \hat{n}_{\perp} + v_{\|} \hat{n}_{\|}$$

Electrons and Holes in germanium

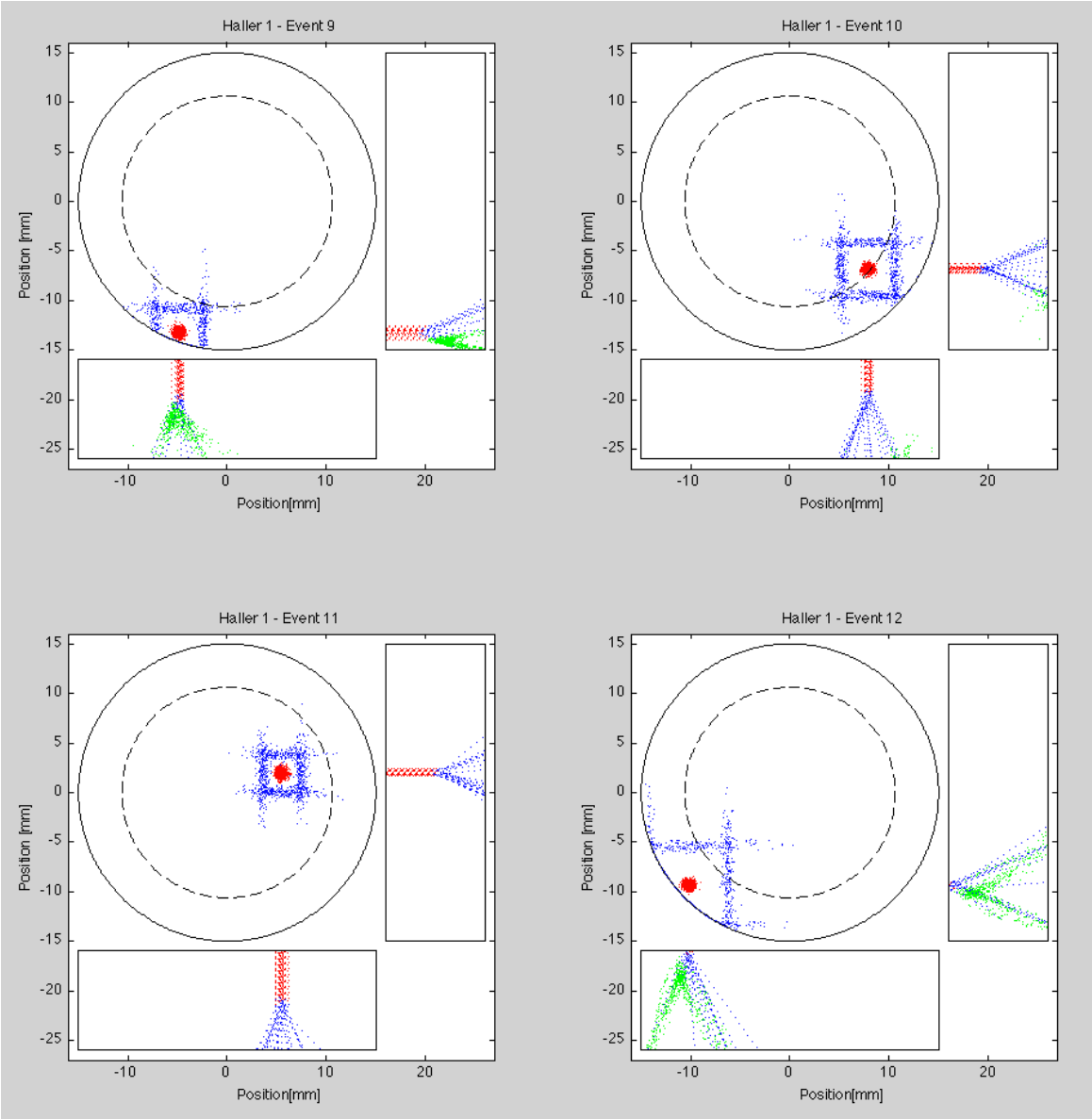




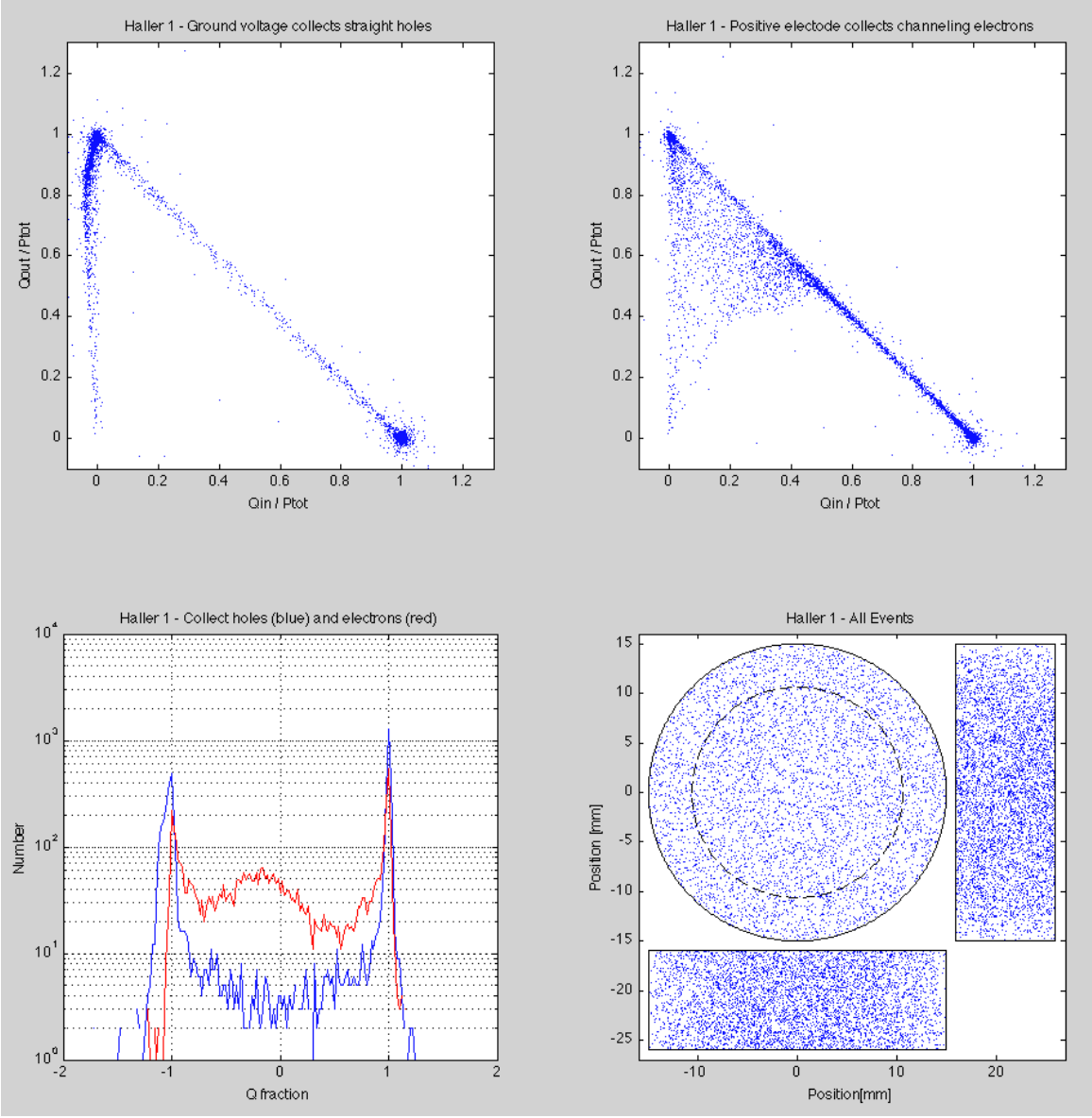




Oblique propagation simulation



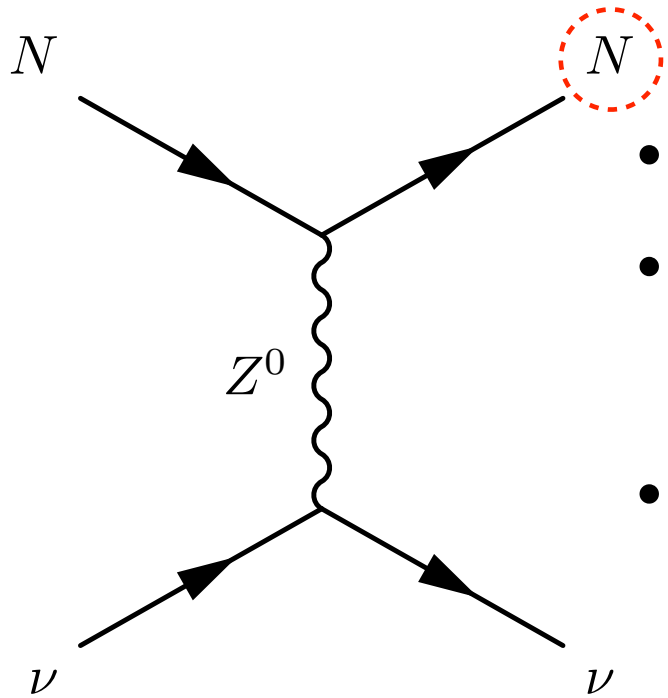
Qualitatively similar features



Summary

- Detector Monte Carlo follows electrons and holes through lattice and use simple valley model for oblique propagation and phonon emission. (see also A. Broniatowski - http://hal.in2p3.fr/in2p3-00674793)
- Recompute electron scattering kinematics for elliptical valley model.
- For electric field greater than about 5 V/cm, inter-valley transitions become important making oblique propagation less pronounced, since the sum of all four valleys is again isotropic.
- Possible that directionality of primary imprinted in distribution of electrons in four valleys.

Coherent Neutrino-Nucleus Elastic Scattering



- Standard Model Process
- Independent of flavor
- $\sigma_{\nu N \to \nu N} \simeq \frac{G_F^2}{4\pi} N^2 E_\nu^2$

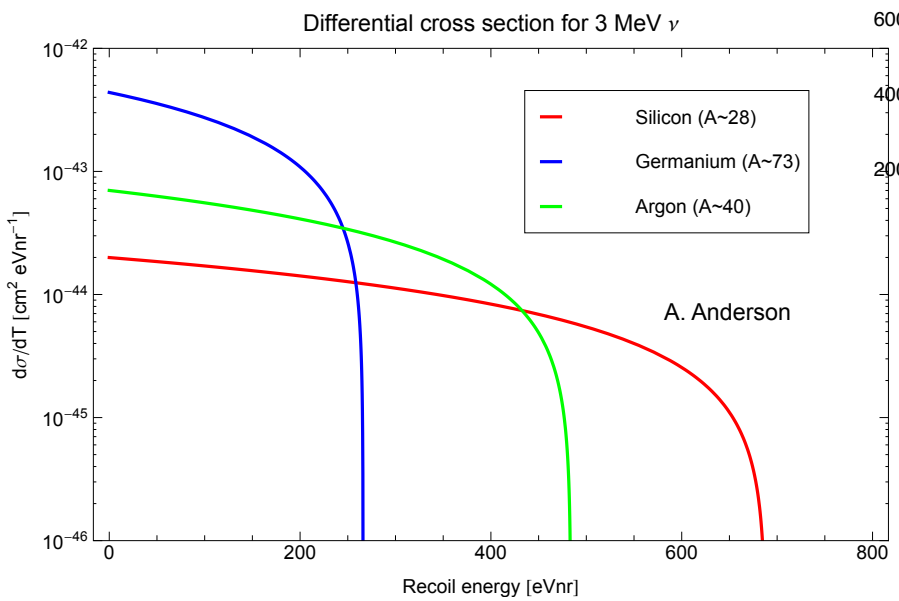
$\sigma_{\bar{\nu} N \to \bar{\nu} N}$	E_ν=3MeV
Ge	6.0×10^{-41} cm^2
Ar	1.8×10^{-41} cm^2
Si	7.4×10^{-42} cm^2
$\sigma_{\bar{\nu} p \to e^+ n}$	4.5×10^{-43} cm^2

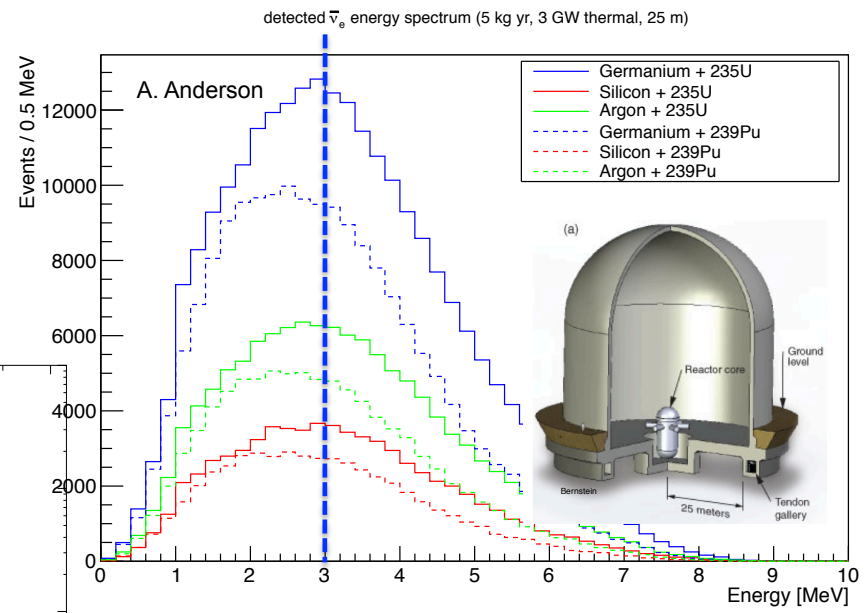
CNS - Recoil Energy Scale

- Never Been Measured!
- $M_N >> E_\nu$ & 4 momentum conservation dictates:

$$\Delta P \lesssim 2P_\nu$$

$$\Delta E \lesssim \frac{\Delta P^2}{2M_n} = \frac{2E_\nu^2}{M_n c^2}$$





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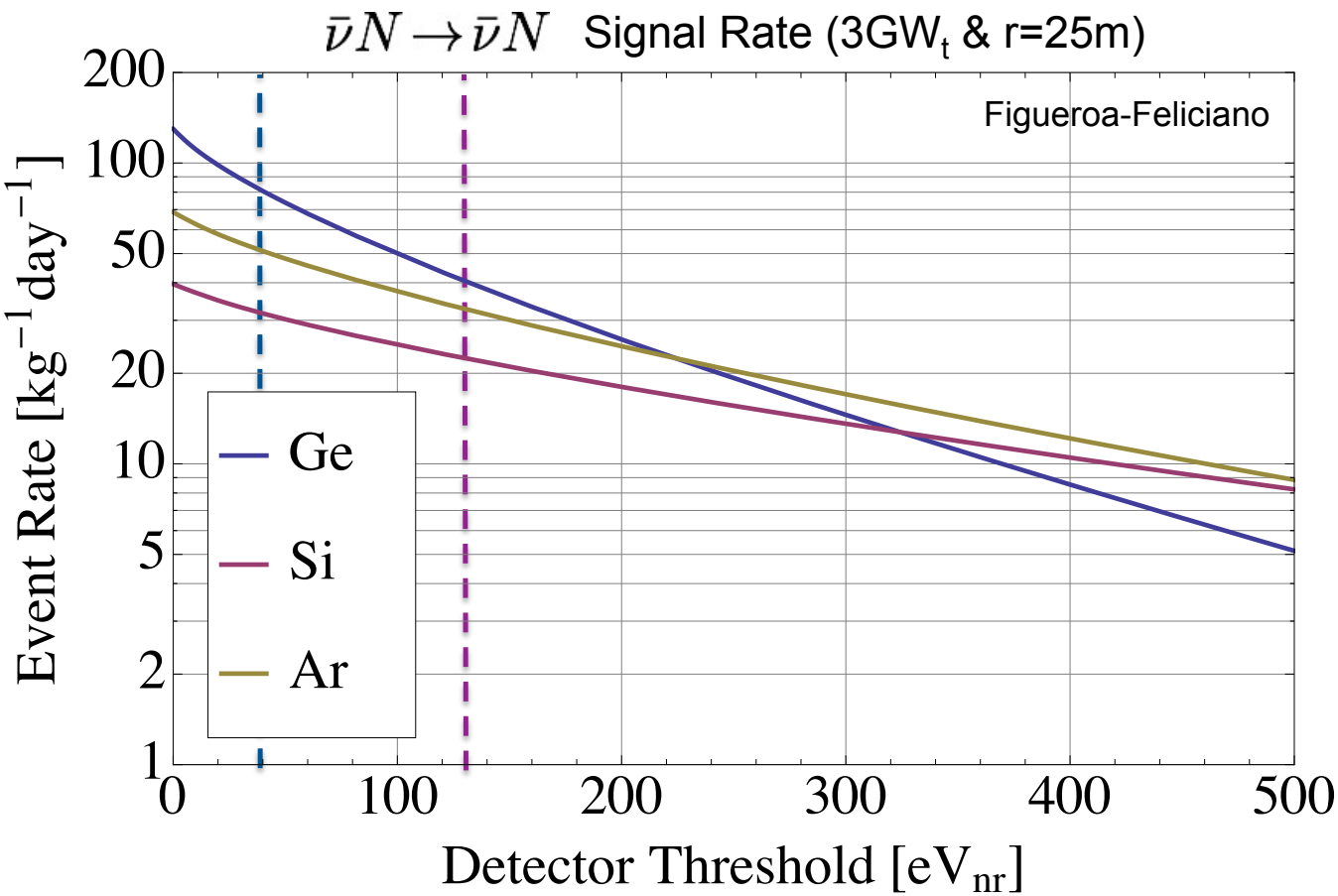
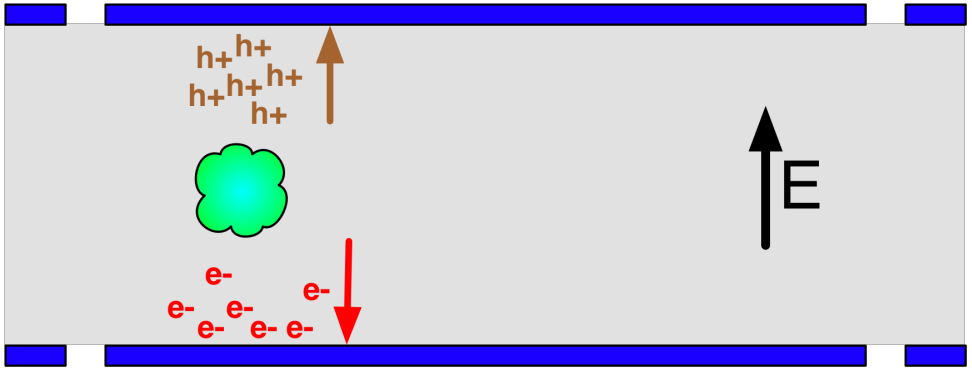
CNS - Reactor Trigger Thresholds



- Reactor Experiment Trigger Threshold Requirements
  - Si: 130eV$_{nr}$
  - Ge: 40eV$_{nr}$

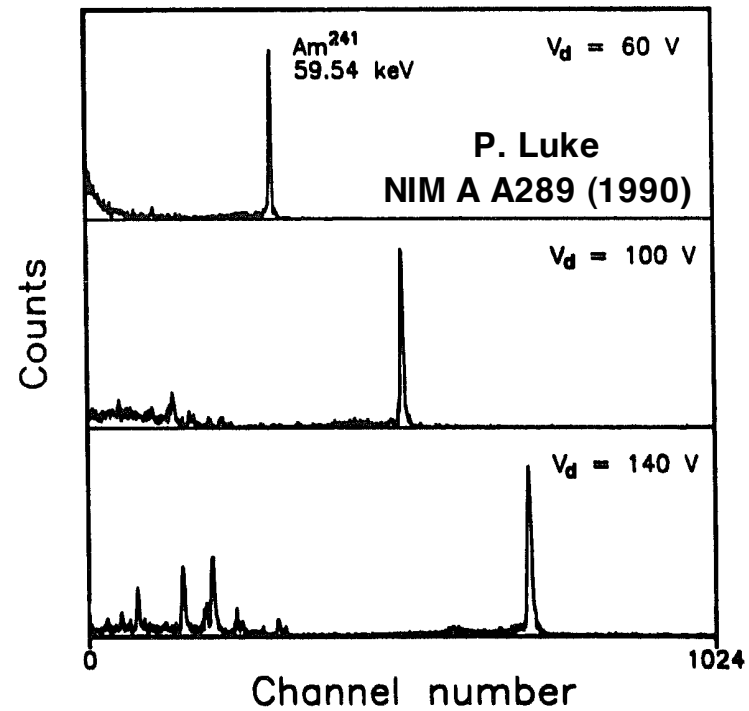
Measure Single Electron-Hole pairs



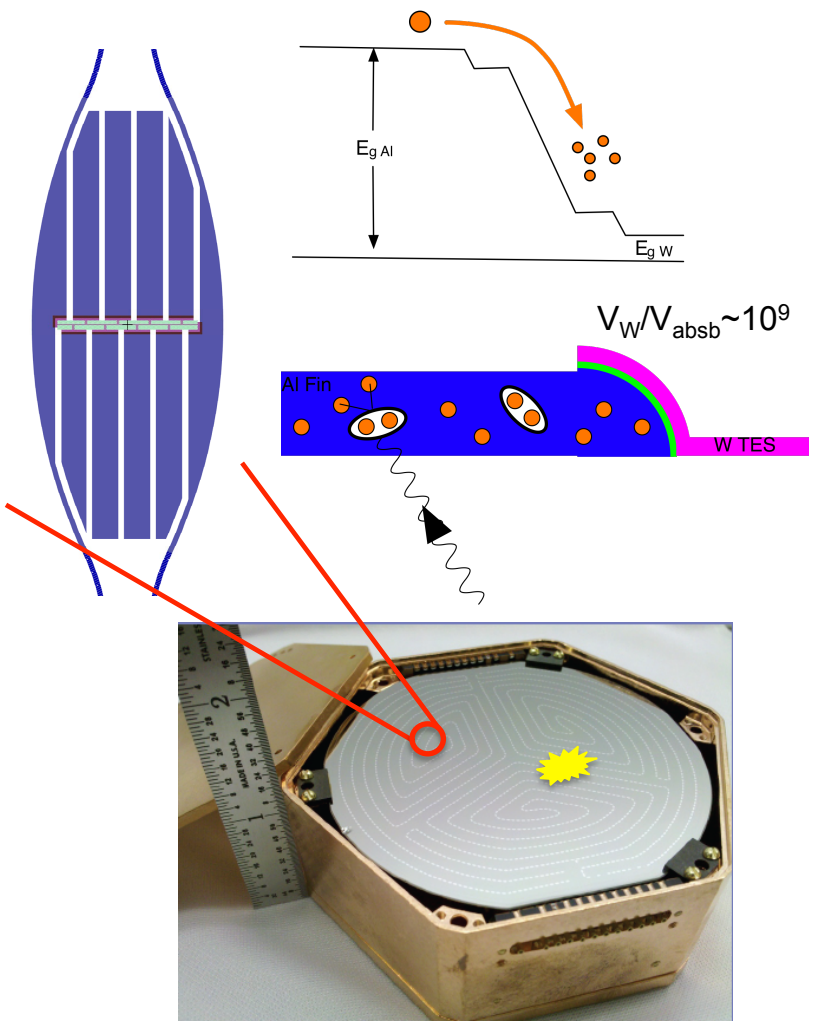
- **Luke**-Neganov Gain

$$E_{tot} = E_r + E_{luke}$$
$$= E_r + n_{eh} e V_b$$
$$= E_r \left(1 + \frac{eV_b}{\epsilon_{eh}}\right)$$

- Field Emission
  - E_b < 25V/cm
  - V_b < 75V for 1” **(best measurement)**
- **Requirement: $E_{trigger}$ ~ 50eV**



Athermal Phonon Detection Principles



- Become insensitive to $C_{absorber}$ by collection and concentration of Phonons
- More Complex
- Collection efficiencies (ε)
  - Theoretical Max: ~40%
  - Best Measured: 20±4%
  - CDMS II: 1-4%
  - SuperCDMS <ε>: ~12±3%
  - Active Research Area for Stanford SuperCDMS
- Not New -> CDMS technology (10+ yrs)

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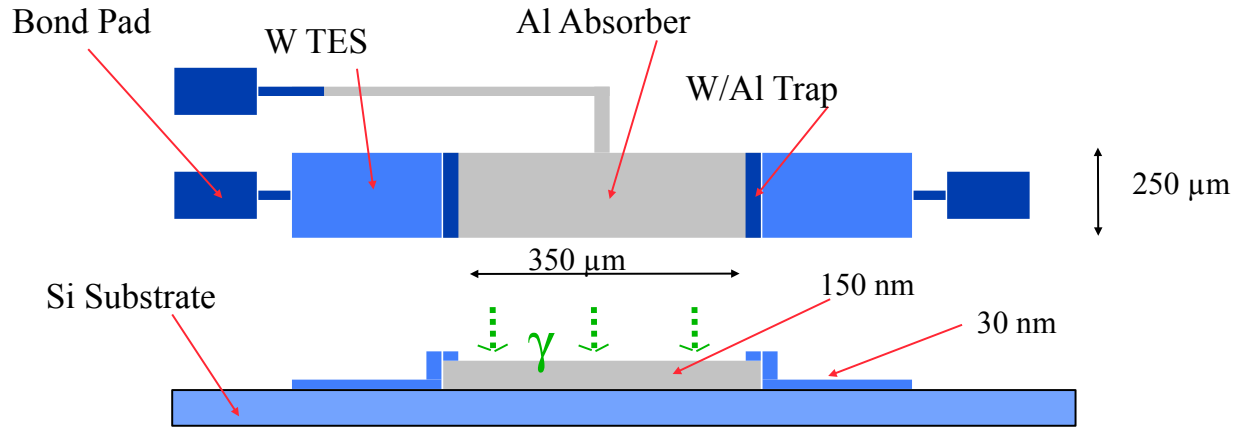
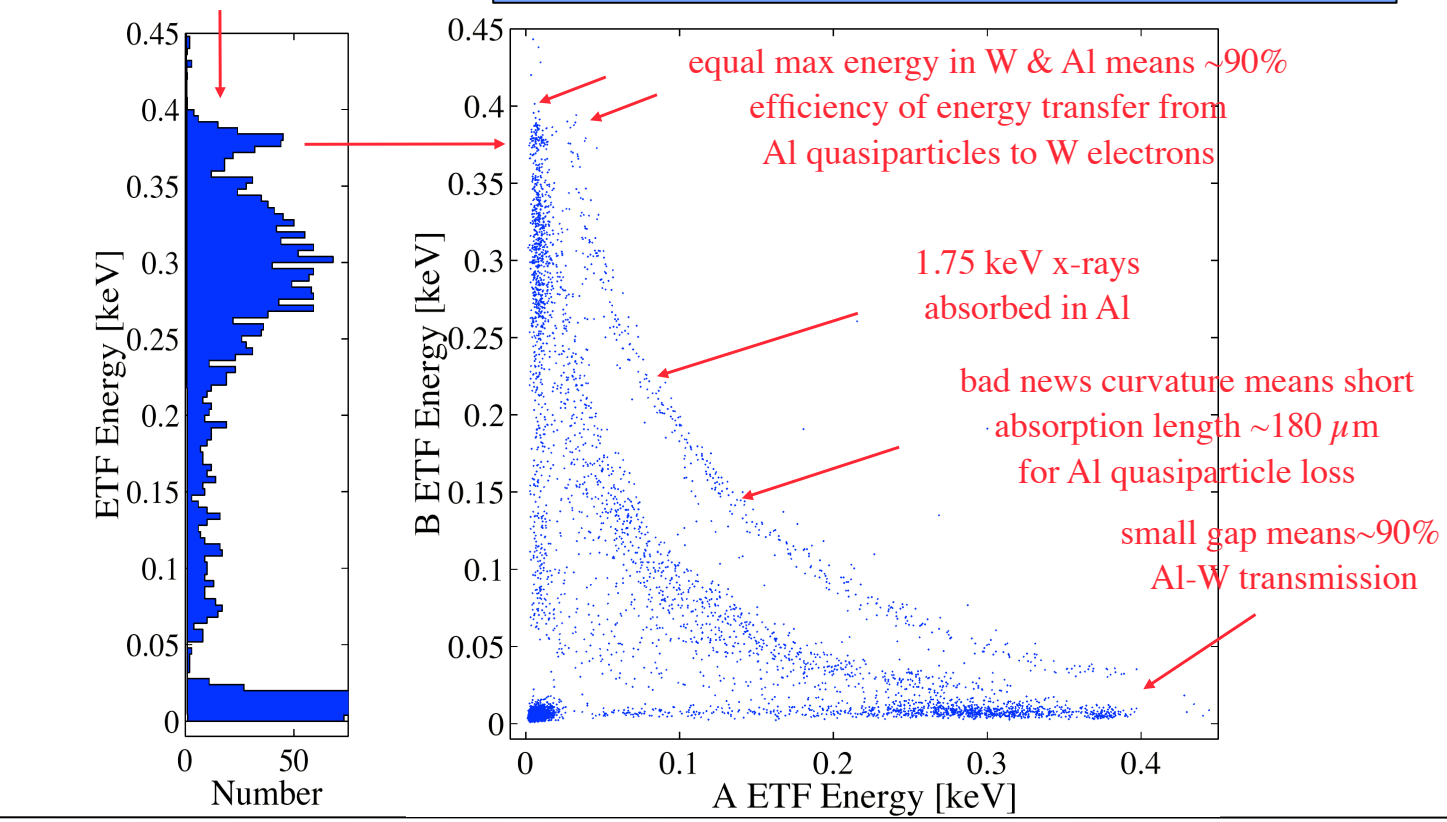
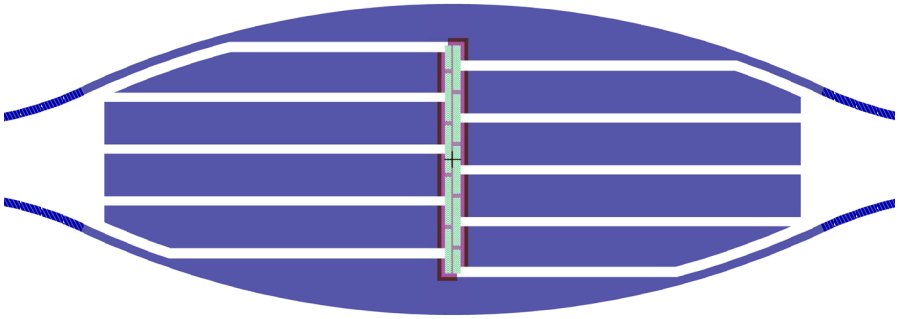
Quasiparticle Loss Measurement

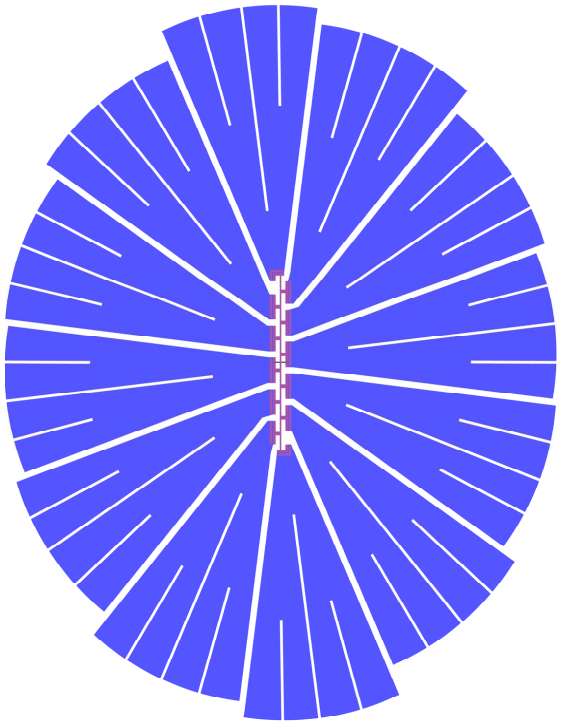
- Test Structures





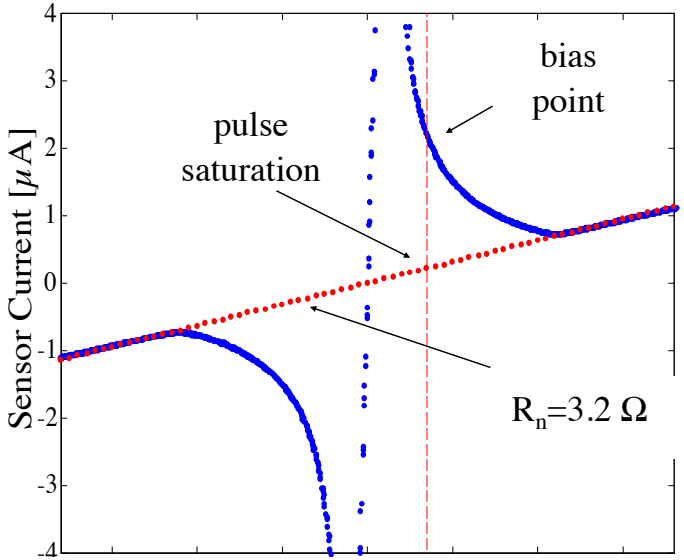
Further Optimization of Al Fins

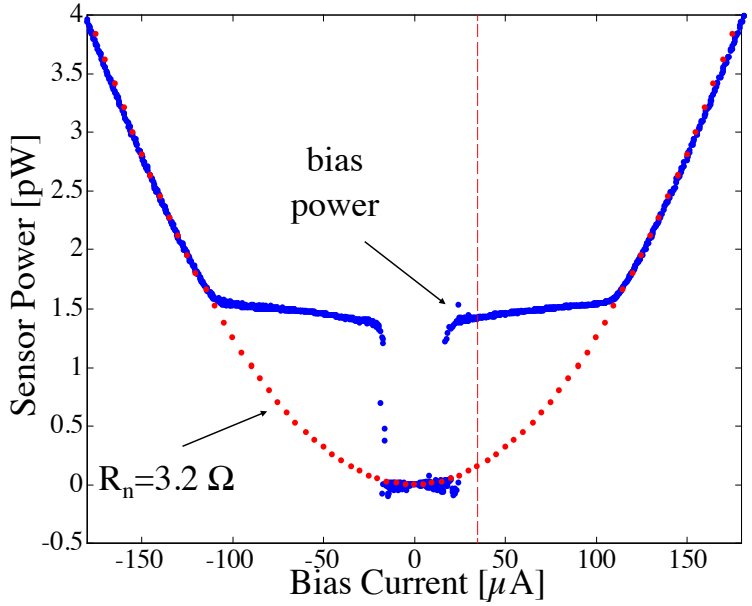


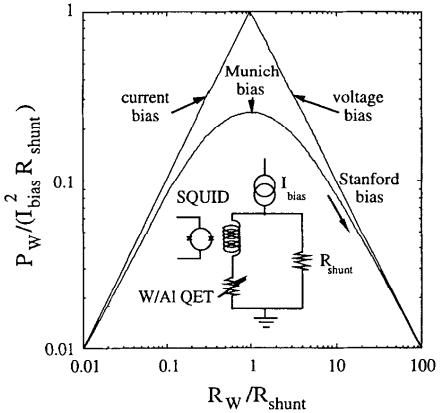


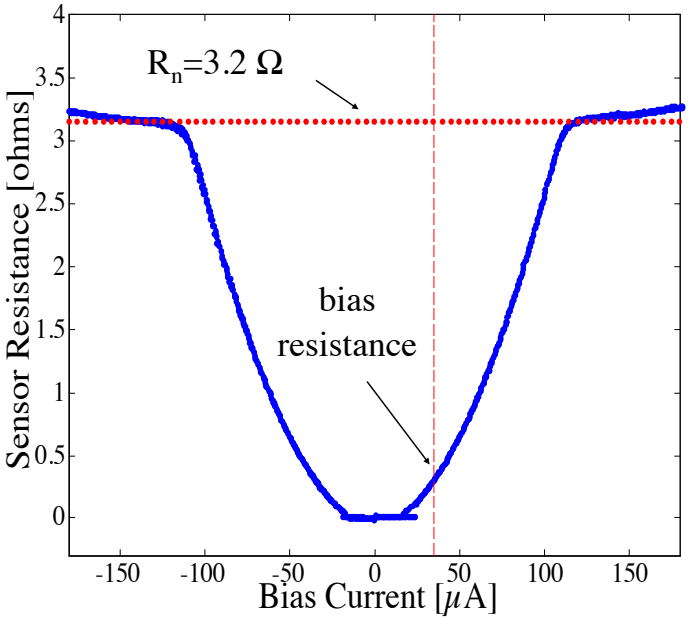
- QP trapping in Al antenna
  - L_{diff} ~ 180um
- Optimally use area near TES

Characterize Performance of TES



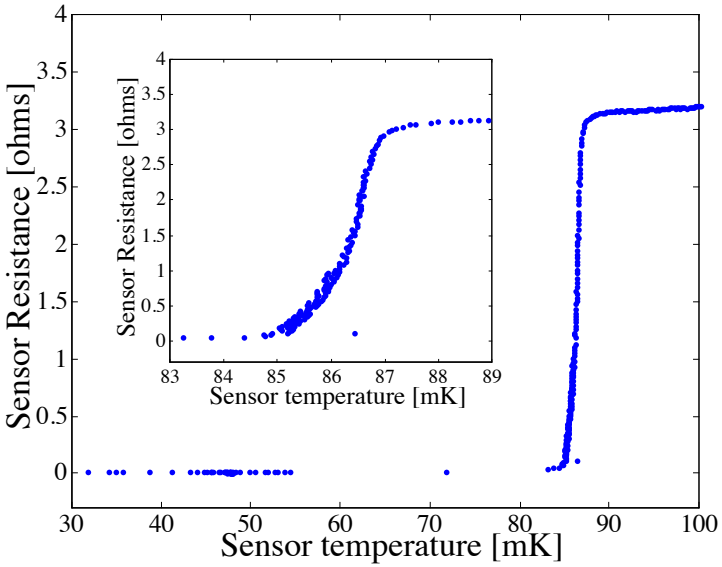






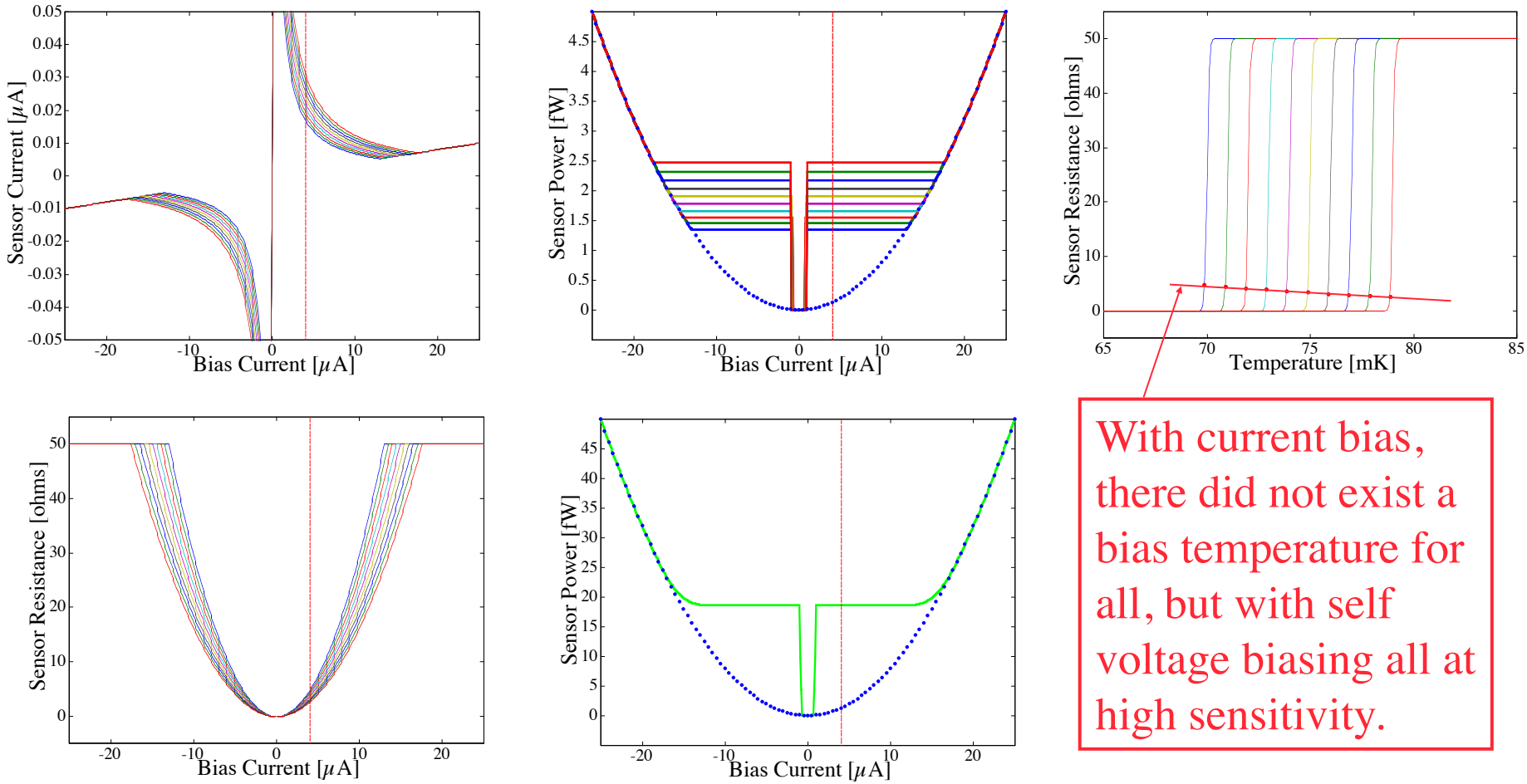
We calculate transition width from power curve using

$$P_J = \Sigma\left(T_e^5 - T_{ph}^5\right)$$



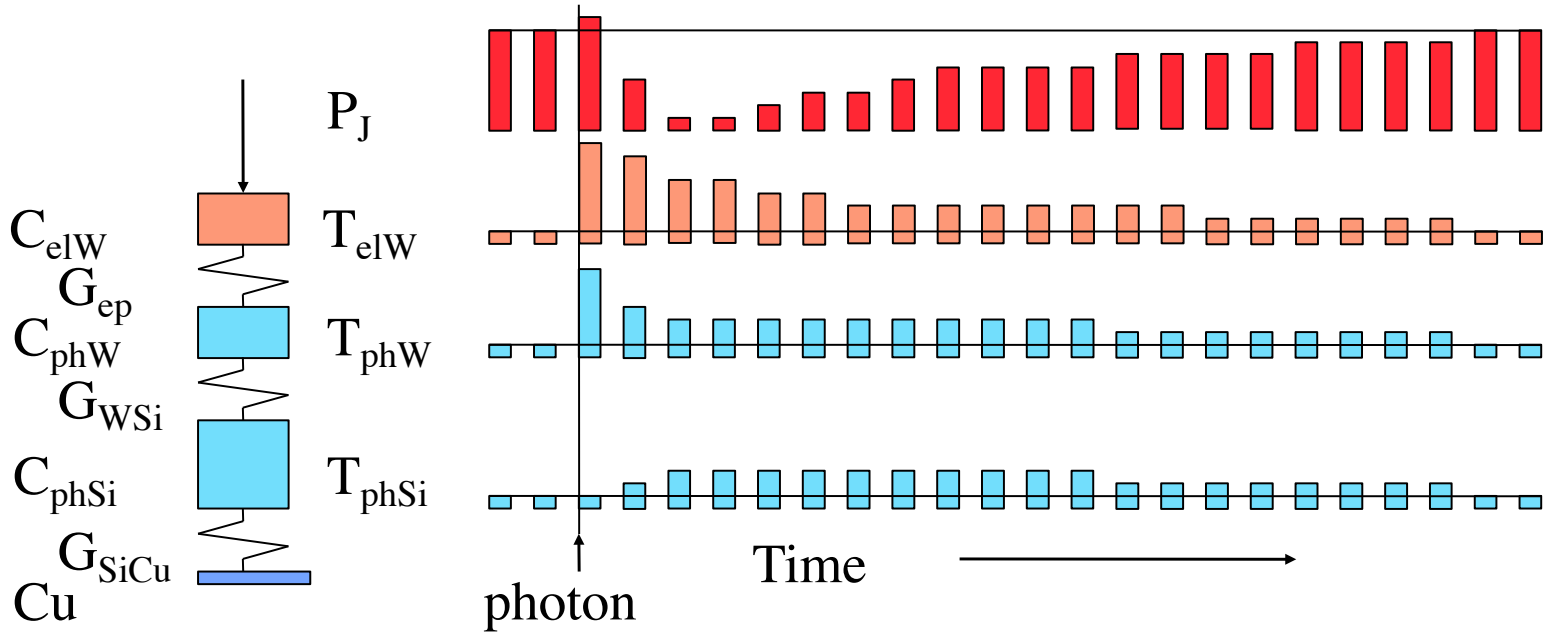
Transition Temperature Gradient Problem

- Voltage biased TES sensors where invented to solve the Tc gradient problem for large area sensors



With current bias, there did not exist a bias temperature for all, but with self voltage biasing all at high sensitivity.

Thermal Model



- Electrothermal Feedback
  - Voltage bias intrinsically stable

$$C\frac{dT}{dt} = \frac{V_B^2}{R} - \Sigma\left(T_e^n - T_{ph}^n\right), \quad n = 5$$

electron-phonon interaction limits conductance at low temperature

  - Fast response

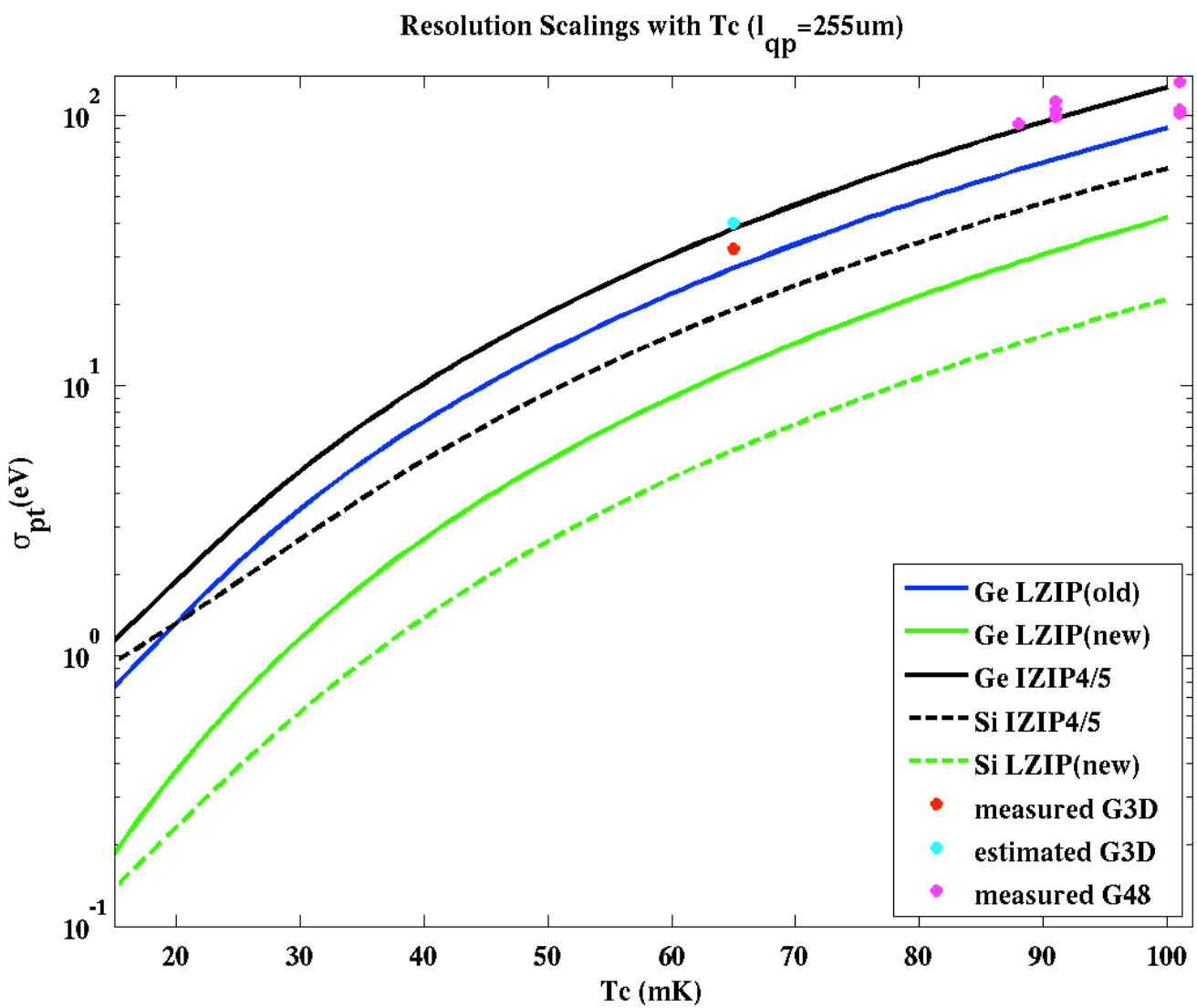
$$\tau_{etf} = \frac{\tau_0}{1+\alpha/n}, \quad \tau_0 = \frac{C}{g}, \quad g = n\,\Sigma\,T_e^{n-1}$$

  - High Sensitivity

$$\Delta E_{FWHM} = 2.355\sqrt{4k_B\,T_e^2\,C\sqrt{\tfrac{n}{2}}/\alpha} = 2.355\sqrt{4k_B\,T_e\,P_J\,\tau_{etf}\sqrt{\tfrac{n}{2}}}$$

$$\text{For } E_{sat}\left(\sim CT_e/\alpha = P_J\,\tau_{etf}\right) = 10\text{ keV then } \Delta E_{FWHM} = 1.1\text{ eV}$$

Optimistic Resolution Estimates



- Low Tc estimates significantly effected by $\alpha(T_c)$ & $\beta(T_c)$
- Baseline Resolution
- Position Systematics ?
  - SuperCDMS 3%

Summary

- Oblique propagation of electrons in Ge
  - need to understand for correct model of performance
  - may provide some directionality information in future
- Interesting science applications at low energy
  - neutrino-nucleus coherent scattering
  - searches of sterile neutrinos
  - limits on neutrino magnetic dipole moment
  - ultra-light dark matter candidates (~MeV)
- Sub - 100 eV thresholds seem technically possible
  - Tc^3 scaling for athermal phonon detectors shown
  - Optimize detector design to maximize phonon collection